

SYSTEM AND METHOD FOR RECOVERING POTENTIAL ENERGY OF A  
HYDROGEN GAS FUEL SUPPLY FOR USE IN A VEHICLE

(1) FIELD OF THE INVENTION

5        This invention relates to a system and a method for  
recovering potential energy of a hydrogen gas fuel supply  
in a vehicle and more particularly, to a system and  
method which uses an expander, compressor and a  
motor/generator to utilize the potential energy stored  
10    within hydrogen gas that is supplied to a fuel cell in  
order to provide pressurized air to the fuel cell and to  
generate electricity, thereby improving the efficiency  
and the fuel economy of the vehicle.

(2) BACKGROUND OF THE INVENTION

15        In order to reduce automotive emissions and the  
demand for fossil fuel, automotive vehicles have been  
designed that are powered by electrical devices such as  
fuel cells. These fuel cell-powered electric vehicles  
reduce emissions and the demand for conventional fossil  
20    fuels by eliminating the internal combustion engine  
(e.g., in completely electric vehicles) or by operating  
the engine at only its most efficient/preferred operating  
points (e.g., within hybrid electric vehicles).

Many fuel cells consume hydrogen gas and air (e.g.,  
25    as a reaction constituent). The consumed hydrogen and  
air must be properly stored and transferred to the fuel

cell at certain pressures in order to allow the fuel cell and vehicle to operate in an efficient manner.

Vehicles employing these types of fuel cells often include systems and/or assemblies for storing and transmitting hydrogen gas and air to the fuel cell. Particularly, the hydrogen gas is typically stored within a tank at a relatively high pressure and with a relatively high amount of potential energy. The hydrogen gas is then transferred to the fuel cell by use of several conduits and several pressure-reducing regulators which lower the pressure of the gas by a desirable amount. While the pressure of the hydrogen gas leaving the fuel tank is substantially lowered prior to entering the fuel cell, it is above normal atmospheric pressures which is required for efficient operation. The air that is communicated from the fuel cell is obtained at atmospheric pressures and must be pressurized or otherwise driven through the system in order to ensure proper and efficient fuel cell operation. This pressurization and/or driving of air through the system is typically performed by use of one or more compressors or turbines. These compressors or turbines require electrical energy for their operation, and therefore drain the vehicle's battery and use generated electrical energy, which could otherwise be used to power the vehicle's electrical components and accessories.

There is therefore a need for a new and improved system and method for use with a fuel cell powered vehicle which recovers the potential energy stored within pressurized hydrogen gas and which converts that potential energy to mechanical and electrical energy that can be used to drive a compressor, to supplement the electrical power demands of the vehicle and/or to recharge an electrical storage device.

## SUMMARY OF THE INVENTION

A first non-limiting advantage of the invention is that it provides a system and method for recovering the potential energy of the compressed gas stored within a fuel cell-powered vehicle.

A second non-limiting advantage of the invention is that it provides a system and method for recovering the potential energy of the hydrogen gas stored within a fuel cell powered vehicle and which selectively converts the potential energy into mechanical and electrical energy which is selectively used to drive a compressor, supplement the electrical power demands of the vehicle, and/or to recharge an electrical storage device.

According to a first aspect of the present invention, a system is provided for recovering potential energy from a hydrogen gas fuel supply that is used to power a fuel cell within a vehicle. The system includes a fuel tank which stores pressurized gas; a first conduit

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system which selectively and fluidly couples the fuel tank to the fuel cell, effective to allow the pressurized gas to be selectively communicated to the fuel cell; an expander including a turbine which is disposed within the first conduit system and which is selectively and rotatably driven by the pressurized gas, effective to generate torque and lower the pressure of the pressurized gas which is communicated to the fuel cell; a second conduit system which selectively and fluidly couples the fuel cell to a source of air, effective to allow the air to be selectively communicated to the fuel cell; a compressor which is disposed within the second conduit system and which is selectively coupled to and driven by the expander, the compressor being effective to pressurize the air which is communicated to the fuel cell; and an electric machine which is operatively coupled to the expander and the compressor, the electric machine being effective to selectively convert torque generated by the expander into electrical power, and to selectively convert electrical power into mechanical torque for rotating the compressor.

According to a second aspect of the present invention, a method is provided for recovering potential energy stored within a pressurized gas used to power a fuel cell within a vehicle. The method includes the steps of: providing a first conduit system for



DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT OF THE  
INVENTION

Referring now to Figure 1, there is shown a block  
5 diagram of a system 10, which is made in accordance with  
the teachings of the preferred embodiment of the  
invention, and which is effective to recover the  
potential energy which is stored within the hydrogen gas  
which is supplied to one or more fuel cells 12 within a  
10 vehicle 14. Particularly, system 10 is adapted for use  
in combination with a vehicle 14 including one or more  
hydrogen-based fuel cells 12 which provide power to the  
vehicle 14. In the preferred embodiment, vehicle 14 is  
an electric or a hybrid-electric vehicle. In the  
15 preferred embodiment, fuel cells 12 utilize a chemical  
reaction that consumes hydrogen gas to generate  
electrical power. It should be appreciated that while in  
the preferred embodiment of the invention, fuel cells 12  
are of the type which consume hydrogen gas, in other  
20 alternate embodiments, other types of compressed gasses  
can be used to generate power within the fuel cell 12,  
and system 10 would work in a substantially identical  
manner to recover potential energy stored within those  
compressed gasses and provide substantially identical  
25 benefits.

System 10 includes a conventional storage tank 16

which receives and stores hydrogen gas at a relatively high pressure, an expander turbine 18 and a compressor turbine 20 which are each coupled to an electric machine or motor/generator 76, pressure regulators 22, 24, a bypass valve 26, an electrical charge storage device or battery 28, a controller 30, vehicle sensors 32 and electrical switches or switching module 34.

The system 10 further includes a first conduit system having several tubes or conduits that are disposed throughout the vehicle 14 and that selectively carry and transport the hydrogen gas from the tank 16 to the fuel cell 12. Particularly, fuel tank 16 is fluidly coupled to valve 26 by use of conduit 38, and valve 26 is fluidly coupled to expander turbine 18 by use of conduit 40 and to regulator 22 by conduit 42. Expander turbine 18 is fluidly coupled to conduit 42 and to regulator 22 by use of conduit 44, and regulator 22 is fluidly coupled to fuel cell 12 by conduit 46.

A second conduit system fluidly couples fuel cell 12 to a source of air. Particularly, compressor turbine 20 is fluidly coupled to and receives air through conduit 48, and is further fluidly coupled to regulator 24 by use of conduit 50. Regulator 24 is fluidly coupled to fuel cell 12 by use of conduit 52. It should be appreciated that the present invention is not limited to the foregoing conduit systems or configurations, and that in

alternate embodiments, different and/or additional numbers of conduits may be used to interconnect the various components of system 10. For example and without limitation, vehicle 14 may further include exhaust and/or return conduit systems (not shown) which are effective to treat and/or remove exhaust gasses from the vehicle 14 and/or to return unused hydrogen gas to the fuel cell 12.

Controller 30 is respectively, electrically and communicatively coupled to regulators 22, 24 by use of electrical buses 54, 56, to switching module 34 by use of electrical bus 58, to sensors 32 by use of electrical bus 60, to valve 26 by use of electrical bus 62, and to motor/generator 76 by use of bus 66. Switching module 34 is further respectively, electrically and communicatively coupled to motor/generator 76 by use of power bus 64, to battery 28 by use of power bus 68, and to vehicle electrical loads and accessories 72 by use of power bus 70.

In the preferred embodiment, controller 30 is a conventional microprocessor based controller and in one non-limiting embodiment, controller 30 comprises a portion of a conventional engine control unit ("ECU"). In other alternate embodiments, controller 30 is externally coupled to the engine control unit.

Fuel tank 16 is a conventional storage tank which is adapted to receive and store compressed gaseous fuel,



such as hydrogen gas, at relatively high pressures. In the preferred embodiment, expander 18 is a conventional turbine which selectively receives and which is rotatably driven by pressurized gas delivered from tank 16.

5 Expander turbine 18 is selectively and operatively coupled to motor/generator 76 by use of shaft 80 and to compressor turbine 20 by of shaft 80, a conventional clutch 84 and a shaft 82 which is coupled to compressor turbine 20. In one alternate embodiment, expander turbine 18 and compressor turbine 20 are connected by a single shaft. When expander turbine 18 and compressor turbine 20 are mechanically coupled together by use of clutch 84, the rotation or torque produced by expander turbine 18 drives compressor turbine 20. This rotation/torque can also be selectively used by the motor/generator to generate electrical energy in a conventional manner. After passing through expander turbine 18, the hydrogen gas is communicated to fuel cell 12 by way of conduits 44, 42, 46 and regulator 22.

20 In the preferred embodiment, compressor turbine 20 is selectively coupled to and rotatably driven by motor/generator 76 and expander turbine 18. Turbine 20 is in fluid communication with conduit 48 and is effective to "draw in" air through conduit 48 (e.g., from the environment external to the vehicle), to compress or pressurize the air and to communicate the pressurized air

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to fuel cell 12 by use of conduits 50, 52 and regulator 24.

Motor/generator 76 is a conventional electric machine which is capable of both generating electrical power from mechanical torque, and generating torque from electrical power. Particularly, motor/generator 76 is capable of operating in an "electrical power-generating mode" in which the motor/generator 76 receives torque from the rotating expander turbine 18 and converts some of that torque into electrical power (the remainder of the torque is used to drive compressor 20). Motor/generator 76 is also capable of operating in a "torque-producing mode" in which motor/generator 76 receives electrical power (e.g., from battery 28) and converts the electrical power into torque for rotating compressor turbine 20. In the preferred embodiment, motor/generator 76 disconnects compressor 20 from expander 18 (e.g., by deactivating clutch 84) during torque-producing operation and delivers torque only to compressor 20, thereby reducing the amount of torque and electrical power required to drive compressor 20.

In the preferred embodiment, regulators 22, 24 are conventional electronically controlled pressure regulators which respectively control the pressure of hydrogen gas and air which entering into fuel cell 12. Particularly, regulators 22 and 24 receive signals from

controller 30 which are effective to control the operation of regulators 22, 24. Controller 30 controls the amount that the regulators 22, 24 decrease the pressure of gas and air entering into fuel cell 12 based upon vehicle operating data that is received from conventional vehicle operating sensors 32. In alternate embodiments, regulators 22, 24 are mechanically controlled or set regulators.

Sensors 32 comprise conventional and commercially available vehicle operating sensors which measure and/or estimate various vehicle operating attributes, such as the pressure of the hydrogen gas and air within various locations in the system (i.e., within various conduits), the vehicle speed, the torque provided by turbine 18 to motor/generator 76, the engine speed, the amount of fuel remaining in tank 16, the pressure of the fuel within tank 16, and/or the state of charge of battery 28. Sensors 32 measure and/or estimate these attributes and communicate signals representing the measured and/or estimated values to controller 30 which uses the signals to operate electrical switches 34, regulators 22, 24, motor/generator 76 and bypass valve 26 in a desired manner.

Bypass valve 26 is a conventional electronically controlled (e.g., solenoid) valve which allows pressurized gas from fuel tank 16 to be selectively

communicated to expander turbine 18 through conduit 40 or to be selectively communicated directly to regulator 22 through conduit 42. Valve 26 may also be selectively disposed in a closed position in which no gas is allowed to escape from tank 16 through either of conduits 40 or 42.

Electrical switches or switching module 34 includes several conventional electrical switches (e.g., transistors and/or relays) which operate in response to signals received from controller 30 and which allow motor/generator 76 to be selectively and operatively connected to electrical components and accessories 72 and to battery 28. In one non-limiting embodiment, switching module 34 may be integral with controller 30. In another alternate embodiment, switching module 34 may comprise several disparate switches or devices which are each independently connected to controller 30 and which individually receive command signals from controller 30.

In operation, system 10 utilizes the potential energy stored within the hydrogen gas fuel to generate torque and electrical power. Particularly, when the tank 16 is filled, the hydrogen gas is at a relatively high pressure. When the vehicle 14 is operated, the pressure of the hydrogen gas must be substantially reduced prior to being transferred to fuel cell 12. When the tank 16 is substantially filled, this pressure reduction is

performed by channeling the pressurized gas through expander turbine 18. Particularly, controller 30 sends a signal to valve 26, effective to cause valve 26 to channel the gas through conduit 40. When the pressurized gas flows through expander 18, it is effective to both desirably reduce the pressure of the gas and to generate torque and rotatably drive expander 18, thereby driving compressor 20 and generating power within motor/generator 76. In this manner, the potential energy stored within the compressed gas is desirably captured and converted into mechanical and electrical energy. Based upon vehicle attribute or operating data received from sensors 32, controller 30 sends signals to motor/generator 76, effective to control the amount of electrical energy generated by the motor/generator 76. For example and without limitation, when tank 16 is substantially filled, motor/generator 76 is allowed to operate with a relatively high electrical power output. As the pressure of the hydrogen gas within tank 16 and conduits 38, 40 begins to decrease, a higher percentage of the torque generated by expander 18 is used to rotatably drive compressor 20 in order to maintain a desired air pressure value within conduits 50 and 52 (e.g., less torque is converted into electrical power).

Controller 30 also controls switches 34, in order to direct the generated power to electrical components and

accessories 72, effective to provide electrical power to one or more conventional vehicle electrical loads or accessories 72 and/or to battery 28, effective to recharge the battery 28. Controller 30 determines where  
5 to direct the generated electrical power based upon the amount or level of power being generated, and the power requirements or needs of the various components 72 and the state of charge of battery 28. The priority and/or sequence in which the various components 72 and battery  
10 28 receive power may be selectively programmed into controller 30 and may be based upon any desirable design considerations. Controller 30 will also source electrical power directly from the battery 28 to the motor/generator 76 in the event that sufficient torque is  
15 not being received from the expander 18 to drive compressor 20 at a certain desired level.

After the compressed hydrogen gas passes through expander 18, it traverses conduits 44 and 42 and enters "low pressure" pressure-reducing regulator 22 which  
20 lowers the pressure of the gas to a predetermined and/or calibratable level which is necessary for the optimal performance of fuel cell 12 and which may be determined based upon the attributes of fuel cell 12. In the preferred embodiment, controller 30 selectively alters  
25 the amount that pressure-reducing regulator 22 lowers the pressure of the hydrogen gas, based upon vehicle

attribute or operation condition data, and based upon the pressure of the gas after it traverses expander turbine 18, which can be sensed in a conventional manner (e.g., by use of conventional pressure sensors (not shown)).

5           Controller 30 further controls the operation of "low pressure" pressure-reducing regulator 24 which ensures that the pressure of the compressed air entering fuel cell 12 is equal to a predetermined value which is necessary for optimal performance of fuel cell 12.

10           As the vehicle 14 is driven and the fuel supply is depleted, the pressure of the hydrogen gas within the system decreases. Controller 30 monitors this pressure by use of sensors 32 and when the pressure falls below a certain predetermined and/or calibratable level,  
15           controller 30 generates a signal to valve 26 effective to cause the hydrogen gas from tank 16 to bypass expander 18 and to flow directly to pressure-reducing regulator 22 through conduit 42. System 10 performs this "bypass" function to ensure that pressure of the hydrogen gas  
20           entering fuel cell 12 is sufficient for optimal performance of the fuel cell 12. That is, when the pressure of the gas in tank 16 falls below a certain level, the pressure drop over the expander turbine 18 may cause the pressure of the hydrogen gas to fall below a  
25           value which is required for optimal performance of the fuel cell 12. In these situations expander 18 is

bypassed and pressure-reducing regulator 22 is accordingly adjusted to provide the desired pressure decrease. Additionally, during these "bypass" operating modes, controller 30 communicates signals to switches 34  
5 and motor/generator 76, effective to source electrical power from battery 28 to motor/generator 76 and to cause motor/generator 76 to operate in a torque-producing mode (e.g., as a motor), thereby driving compressor 20 at a desired level. In the preferred embodiment, controller  
10 30 also signals motor/generator 76 to deactivate clutch 84, effective to disconnect compressor 20 from expander 18, thereby allowing all of the motor-generated torque to be used to drive compressor 20.

In this manner, system 10 efficiently utilizes and  
15 recovers the potential energy stored within the compressed hydrogen gas by use of expander turbine 18 and motor/generator 76. This potential energy is selectively converted into mechanical torque and electrical power which is used to drive compressor 20 and to selectively  
20 power various components and/or to recharge the vehicle's battery 28. System 10 further eliminates the need for a "high-pressure" pressure-reducing regulator, by desirably lowering the pressure of the hydrogen gas by a substantial amount (e.g., by at least a factor of 10)  
25 prior to the gas passing through low pressure step-down regulator 22 and into fuel cell 12. System 10 also



provides the flexibility to bypass the expander 18 in certain situations, thereby substantially guaranteeing that the gas entering fuel cell 12 will be of a sufficient pressure for optimal performance.

5        It is to be understood that the invention is not to be limited to the exact construction and/or method which has been illustrated and discussed above, but that various changes and/or modifications may be made without departing from the spirit and the scope of the invention.